

## THE MEGAGEOMORPHOLOGY OF THE RADAR RIVERS OF THE EASTERN SAHARA

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## I. SIGNIFICANCE OF THE RADAR RIVERS

The Eastern Sahara (Fig. 1) is devoid of surface drainage -- this unusual characteristic distinguishes its morphology from that of most other desert regions where running water dominates landscape development (Peel, 1939). Cyclic aridity, which is responsible for the obscuring eolian blankets and wind-erosion effects, had set in by the Pliocene-Pleistocene transition, about 2 million years ago (Williams, 1982). SIR-A/B reveals, however, that the "bull's-eye" of aridity in North Africa underwent a long prior history of erosion by southwestward-trending Tertiary streams (McCauley et al., 1986; Schaber et al., 1986).

Figure 2, derived from SIR-A/B and Landsat images and the literature, shows the major presently known paleodrainages in the Eastern Sahara. Of particular importance in this compilation is the presence of the Abu Ballas Divide. This structural arch contains Jurassic continental clastics that crop out discontinuously along a topographically subdued prong and extend eastward from the Gifl Kebir Plateau to the Dakhla-Kharga region, south and west of the Limestone Plateau. Westward-flowing drainages lying to the south of this post-Tethys divide would have been shepherded away from the Mediterranean to take other routes to the sea or to intracontinental basins.

This compilation (Fig. 2) permits consideration of the key questions: Where did the radar rivers come from and where did they go? The detailed work done along the Nile Valley in the past three or more decades (Said, 1981, 1982) is of limited assistance in this effort because the Nile is chiefly a late Tertiary-Quaternary feature. The various rivers that once occupied the Nile Trough are relatively young (late Miocene to Quaternary), and they developed separately from the older (late Eocene) westward-trending radar rivers. The oldest of the Niles, the Eonile (Said, 1981), is relevant to the radar river problem because during the Messinian event it cut a canyon from Cairo to Aswan that was longer and deeper than the Grand Canyon of the Colorado River in Arizona. This deep southward incision by the Eonile in the late Miocene created a new drainage barrier in Egypt that severely affected the subsequent history of the radar rivers.

Analysis of SIR-A data led McCauley et al. (1982) to suggest that the radar rivers, because of their southwestward trends, once flowed into the Chad Basin. This key North African feature is a regional structural low formed in the Early Cretaceous in response to initial opening of the South Atlantic (Browne and Fairhead, 1983). The problem of the origin of headwaters for the radar rivers was less tractable. The idea that the source areas of the radar rivers might originally have been the same as those (The Ethiopian Highlands) later captured by the Nile was proposed tentatively. A more extensive review of the Cenozoic tectonic history of North Africa reveals no reason now to suppose that the Central African tributaries of the present Nile were ever connected to the large alluvial valleys in southwestern Egypt and northwestern Sudan.

New insights into the problem of determining the source areas of the radar rivers are provided by Issawi (1983). An analysis of the relations of wadis such as the Allaqi, the Qena, and those of the Kom Ombo area, all east of the present Nile, points to the Red Sea Hills in Egypt and Sudan as a logical source area for the radar rivers. These valleys mark, in part, the courses of old westward- and southward-flowing consequent streams. They are the descendants of a more ancient drainage system that developed independently of the successive rivers that later occupied the Nile Trough. These streams and other westward-flowing consequent drainages, which came from the flanks of the Red Sea uplift prior to integration of the Nile Trough, in either middle or late Tertiary time must have run out onto the continental slope of a then more simple African landscape. The radar rivers, when put into the context of the plate tectonics of North Africa, prove to be the missing links to a previously unrecognized, now-defunct drainage system of continental proportions.

## II. A TRANS-AFRICAN DRAINAGE SYSTEM

The unusual surficial characteristics of the Eastern Sahara, particularly its present hyperaridity and unique eolian veneer, are products of progressive Quaternary desiccation. The region is not a distinct geologic entity. Its pre-Quaternary history is inseparable from the now-well-documented sequence of Tertiary tectonic and volcanic events that shaped North Africa as a whole. The more detailed picture of the history of the radar rivers than possible in our earlier report (McCauley et al., 1982) results from post-SIR-A field work and a number of recent key papers on the tectonics of North Africa, particularly the Central African Rift System (Bermingham et al., 1983).

Shortly after or simultaneously with the regression of the Eocene Tethys Sea from southwestern Egypt, the Afro-Arabian (Red Sea) Rift began to form, about 30 to 40 million years ago; the first movements occurred as early as lower middle Eocene. A sequence of events involving doming, rifting, sedimentation, magmatism, and tectonism then took place along the northeast edge of Africa and profoundly affected this newly emergent landscape (Table 1). More than 2000 m of uplift of the crystalline basement and the Mesozoic and early Tertiary sedimentary cover occurred in the Red Sea Hills region. A number of large, roughly northward-trending troughs such as the Qena and the Nile, along with east-west structures like the Abu Ballas Divide, formed in response to the opening of this new oceanic rift. The Red Sea Hills (Fig. 1) would have been the highest mountains in northeastern and central Africa during Oligocene to middle Miocene time, because the great intraplate volcanic complexes such as the Darfur and Tibesti had not yet developed. These northward-trending Red Sea massifs sloped to the west, toward the older Cretaceous sedimentary basins of north-central Africa, and the consequent streams emerging from the Red Sea Hills were controlled by these regional slopes (Fig. 3).

The Tertiary climate of Egypt, and by inference that of much of North Africa was wet; a dense vegetation cover and moderate to intense chemical weathering suggest warm temperatures. Discharge would have been substantial off the continental slopes of the Eastern Sahara and the developing Ethiopian-Afar volcanic complex. A family of westward-flowing, vigorous branch streams that extended many hundreds of kilometers downstream from their source areas must have developed. These streams are probably contemporaries

of the streams in northern and central Egypt that deposited the gravel spreads of Oligocene age described by Said (1981, 1983) and Salem (1976). Unlike those streams, however, the consequent streams from the Red Sea Hills would have flowed not only over the marine sediments of the Limestone Plateau, but in southern Egypt and Sudan they would have flowed around and beyond the Tethys embayment to run directly on older, pre-Tertiary surfaces. The radar valleys in southwestern Egypt and northwestern Sudan discovered on SIR images represent the middle reaches of this drainage system.

The earlier Trans-Saharan Seaway that existed between the Tethys and the Atlantic in the Late Cretaceous, and which had closed by early Tertiary time (Kogbe, 1980), may have acted as a palimpsest guidance system for these new rivers as they sought the lowest ground of central North Africa. The trunk streams are well expressed in northwestern Sudan, from whence those trending to the southwest probably found their way into the Boélé-Chad Basins south of Faya. Drainage patterns, however, are confused by later tectonic and volcanic events in the area east of the Ennedi, between the domal uplifts of the Tibesti and Darfur regions. Some discharge into Chad may have been along the Mourdi Valley as previously suggested (McCauley et al., 1982), but more likely paths are the Marhdougoum-Derbeli gaps some 480 km east of Faya and the low regions south of the Ennedi (Figs. 1, 2, and 3).

Grove and Warren (1968) point out that boreholes in the vicinity of present Lake Chad show layers of sand alternating with thicker layers of clay, indicating deposition under fluvio-lacustrine conditions. A hippopotamus jaw, recovered from below 60 m, suggests that the deposits beneath the Paleo-Chad Sea (Mega-Chad) and its shrunken Holocene remnant are of probable Tertiary age.

No evidence is reported of regional ponding of the putative Tertiary drainages in the Chad Basin, as occurred when the Paleo-Chad Sea formed during the height of the last major North African pluvial about 10,000 years ago. At this time, Mega-Chad was about the size of the present Caspian Sea; a reasonably complete shoreline can be traced around it at an elevation of about 320 m. The waters of this great basin have risen as high as 380 to 400 m and the the Logone River, a tributary of the present lake, may have acted as a spillway to the Benue. Even today, waters from the shrunken remnant of Mega-Chad are reported to escape by way of a chain of small lakes that lead to the Mayo Kebbi River, a tributary of the Benue (Grove, 1970). The Mayo Kebbi is presently a small river occupying a large valley; it could represent the main mid-Tertiary outlet to the Atlantic of our suggested Trans-African drainage system (TADS).

The Bodélé depression now lies about 180 m below the present level of Lake Chad, and the 500-km-long Bahr el Ghazal that connects them now intermittently flows northeast. As described earlier, the drainages seen on both SIR and Landsat images around the flanks of the Tibesti and Darfur massifs are confused by multiple superposition patterns. Neither of these situations poses any major constraints on the mid-Tertiary drainage system proposed here because the Tibesti and Darfur, along with the intervening high ground of the ennedi, represent an arm of domal uplift related to the Central African Rift System of Browne and Fairhead (1983). The earliest lavas in the

Gebel Marra complex, which now forms the divide between the present Chad and Nile Basins, have been dated provisionally at 13.5 m.y. (Birmingham et al., 1983). The present-day topographic obstacles (domes, structural uplifts, and depressions) did not exist in mid-Tertiary time. The Bahr el Ghazal may represent the much-modified trace of one of the major trunk streams, or be part of the master stream of the Trans-African system that traversed the Chad Basin and flowed into the Atlantic by way of the Benue and the Niger (Fig. 3).

The Benue Trough, which is associated with the opening of the South Atlantic (Burke et al., 1971) and which split the West African and Congo Cratons, had closed by the Late Cretaceous. The Benue Trough has been interpreted by Adighije (1981) as an earlier, abortive attempt to open western Africa into an ocean similar to the later, more successful Red Sea Rift. Regardless of this failure, the trough controls the path of the Benue River, the largest tributary of the Niger River. By late Eocene time deltaic sediments had begun to spread westward down the Benue Valley toward the Atlantic and the present mouth of the Niger River, where they began to form a delta that ultimately grew three times larger than the Nile Delta. This trough, along with the other preconditioning elements described earlier, must have determined the courses of the lower reaches of a continental drainage system that extended some 4500 km from the crest line of the Red Sea Hills to the early Niger Delta (Fig. 3).

Other middle Tertiary branch streams that were originally part of this Trans-African drainage system may have been present in central and southern Sudan. Streams there might have flowed across or to the south of the Darfur area before uplift; the downstream parts of such drainages would have been controlled by the central African Rift System (particularly the Ngaoundere and the Abu Gabra Troughs in Cameroon and Chad). These areas are, however, beyond the scope of our present work.

The active life span of the Trans-African drainages described in this scenario was at least 20 million years (Table 1). The onset of middle Miocene doming and later intracontinental volcanism in North Africa began to disrupt the drainage system. Large segments would have remained active, but how long the drainages might have remained integrated all the way to the Atlantic is beyond speculation. At the end of the Miocene, an unusual set of circumstances (drying up of the Mediterranean) created the Eonile, a vigorous pirate stream in eastern Egypt. The headward (southward) incision of a deep Eonile Canyon (Said, 1982) brought the newly formed, north-flowing Eonile into direct conflict with the older, Atlantic-related Trans-African system. From the coastal cliffs of the Cairo area to Aswan, and possibly as far south as the second cataract of the present Nile, the Eonile beheaded the still-operational parts of the Trans-African drainages from their headwaters in the Red Sea Hills. This fatal blow left only the broad radar river valleys and the scattered "gravel spreads" elsewhere in the Eastern Sahara as testimony to the existence of a once-great transcontinental drainage system. Temporary rejuvenations occurred during the Quaternary pluvials, when episodic overbank flooding occurred on the terraces and small wadis (braided stream complexes and local ponds) formed in the floors of many of the old alluvial valleys. These ephemeral watercourses were utilized by successive groups of early humans until almost the dawn of the historical period, when climatic deterioration made the area virtually uninhabitable.

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Table 1. Geologic framework that affected development of Trans-African drainages. Relevant Pleistocene glacial events, which took place outside North Africa, shown in brackets. (Time scale after Van Eysinga, 1975)

## CENOZOIC ERA

PERIOD AND SUBPERIOD	EPOCH	AGE (m.y.: million years)	INFERRED CLIMATE	KEY GEOLOGIC EVENTS	ARCHAEOLOGY (See Table 1)	GEOMORPHIC SIGNIFICANCE
Holocene		0.005	Onset of present hyperaridity Semiarid (Saharan pluvials)	Desiccation of surface, loss of vegetation, eolian reworking of alluvial sediments Formation of Paleo-Chad Sea Integration of present Egyptian Nile with central African sources	Neolithic	Almost total obscuration of fluvial imprint by active sand sheets and dunefields Last pulses of fluvial activity (RR2 and RR3)
		0.010 0.020				Beginning of modern Nile River Intermittent shedding of gravels from Red Sea wadis across filled alluvial valley of weak Nile River
		0.050	Hyperarid	[Wisconsinan (Wurm) glaciation]	Paleolithic	Episodic calcification of fluvial deposits in Western Desert at 0.018, 0.50, .118, 0.300 m.y.
		0.250	Semiarid (Abassian pluvial)	Deposition of Abbasia Formation		Episodic runoff in incised and anastomosing channels (RR2 and RR3)
			Hyperarid	Deposition of Qena Formation		Intermittent eolian reworking of fluvial sediment into dune fields and sand sheets
Pliocene		1.5	Hyperarid	(Illinoian (Riss) glaciation)		Climatic deterioration. Final demise of now beheaded and tectonically dismembered Trans- African drainage system (RRI)
		2.0 2.5	Wet Tropical (Idfu pluvial) Onset of pro- gressive aridity	Deposition of Idfu Formation (Kansan glaciation)	Pebble tools	
				[Nebraskan glaciation]	-----	
		5.1 6.0		Deposition of 300-1000 m marine sediments in Nile Valley. Refilling of Mediterranean basin. Messinian event: drying up of Mediterranean; 3500-m drop in baselevel for active streams connected to Mediterranean		Aggradation of Nile River Valley from Aswan to delta. Canyon 2500m deep, 700km long cut by Nile River through South Delta block to Aswan. Canyon cutting beheads consequent tributaries of Trans-African drainage in Red Sea Hills
				Domal uplift and volcanism in Hoggar, Tibesti, Darfur, Adamaoua areas		Disruption of Trans-African drainage by creation of new divides between Nile Basin, Chad Basin, and Gulf of Guinea; streams become senile. Wadi Qena flows south, builds fans in depressions of Nile Trough. North- flowing drainages in Nile Trough begin southward extension
Miocene		15.0	Mostly humid(?) with some arid intervals			Maximum development of Trans-African drainage (RRI)
		24.6		Mountains of South Delta block and other uplifts form elevated highlands along coast of northern Egypt and Libya		

Table 1 (contd)

CENOZOIC ERA					ARCHAEOLOGY (See Table 1)	GEOMORPHIC SIGNIFICANCE
PERIOD AND SUBPERIOD	EPOCH	AGE (m.y.: million years)	INFERRED CLIMATE	KEY GEOLOGIC EVENTS		
	Oligocene	38.0	Wet Tropical	Continental conditions prevail: Widespread deposition of fluvial coarse sands and gravels over Eocene limestones in northern Egypt. Episodic volcanism		Initiation of Trans-African drainage pattern from Red Sea Hills southwestward down continental slope to Atlantic via Erdi and Chad Basins and Benue Trough Southwestward continental slope develops across Northeast Africa. Streams consequent to Red Sea Hills begin to form Trans-African drainage net, emptying into Atlantic at paleo-Benue/Niger Delta
	Eocene			Regression of Tethys Sea from North Africa, early doming, rifting of Afro-Arabian shield, and beginning of uplift of Red Sea Hills		
	Paleocene			Tethys Sea Invades Northeast Africa		
MESOZOIC ERA		54.9				Widespread deposits of marine limestones in Northeast Africa (sediments of Limestone Plateau in Egypt, and equivalents in Libya)
		65.0				
CRETACEOUS	Late			Closure of Benue Trough ends marine transgression in southern North Africa		Widespread deposition of continental clastics of Nubia Fm. and equivalents in Northeast Africa
				Trans-Saharan Seaway connects Tethys Sea with Atlantic through Benue Trough at Gulf of Guinea		



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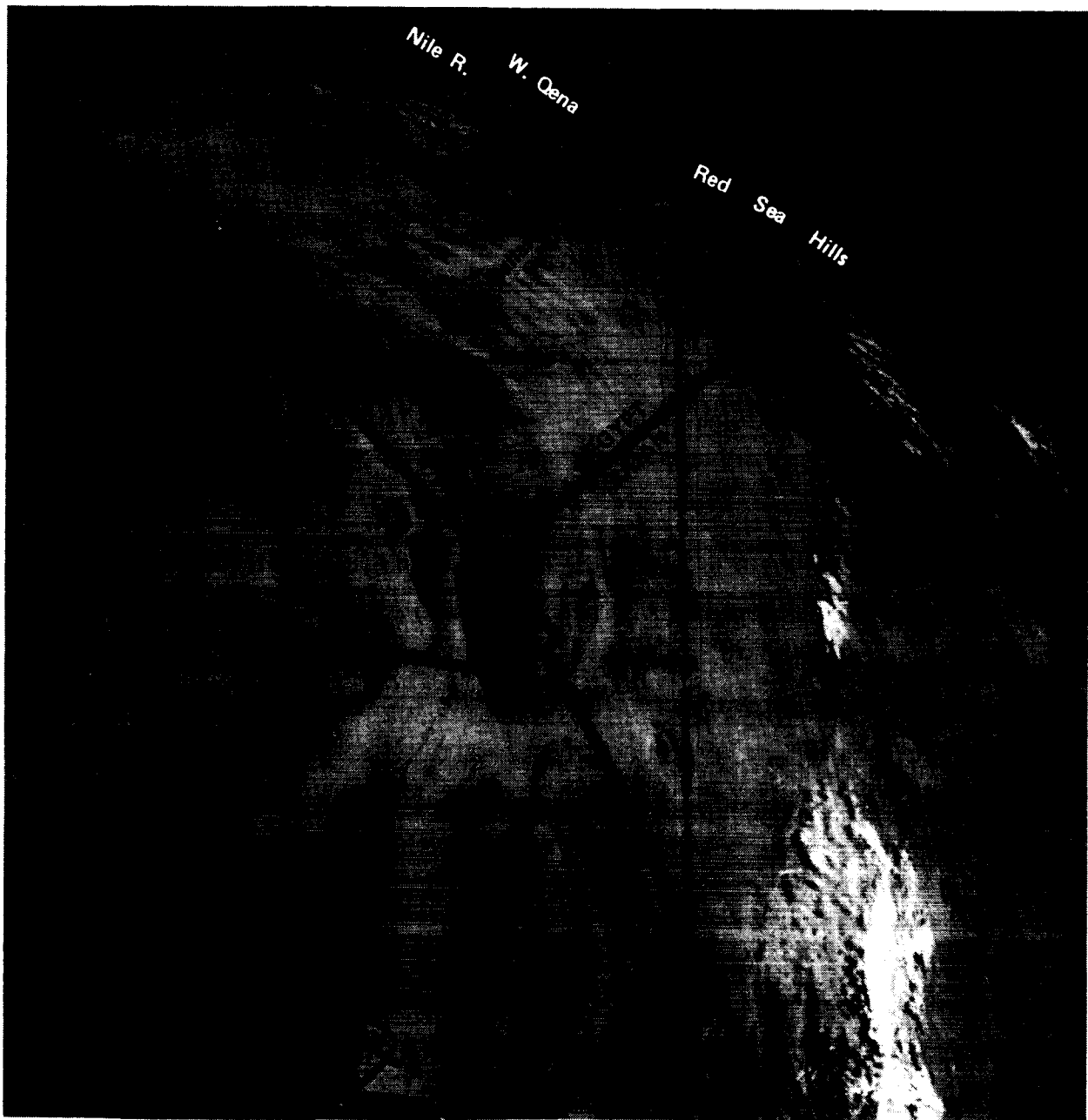


Figure 1. High altitude (Gemini XI) photograph shows the presently hyperarid Eastern Sahara west of the Nile River, and the Red Sea Hills, former headwaters of TADS, to the east. Piracy by the headward-incising Eonile cut off the headwaters of TADS, which once flowed across this now barren, sand-mantled region. SIR-A swath, on which TADS segments were first detected, indicated by dashed line.

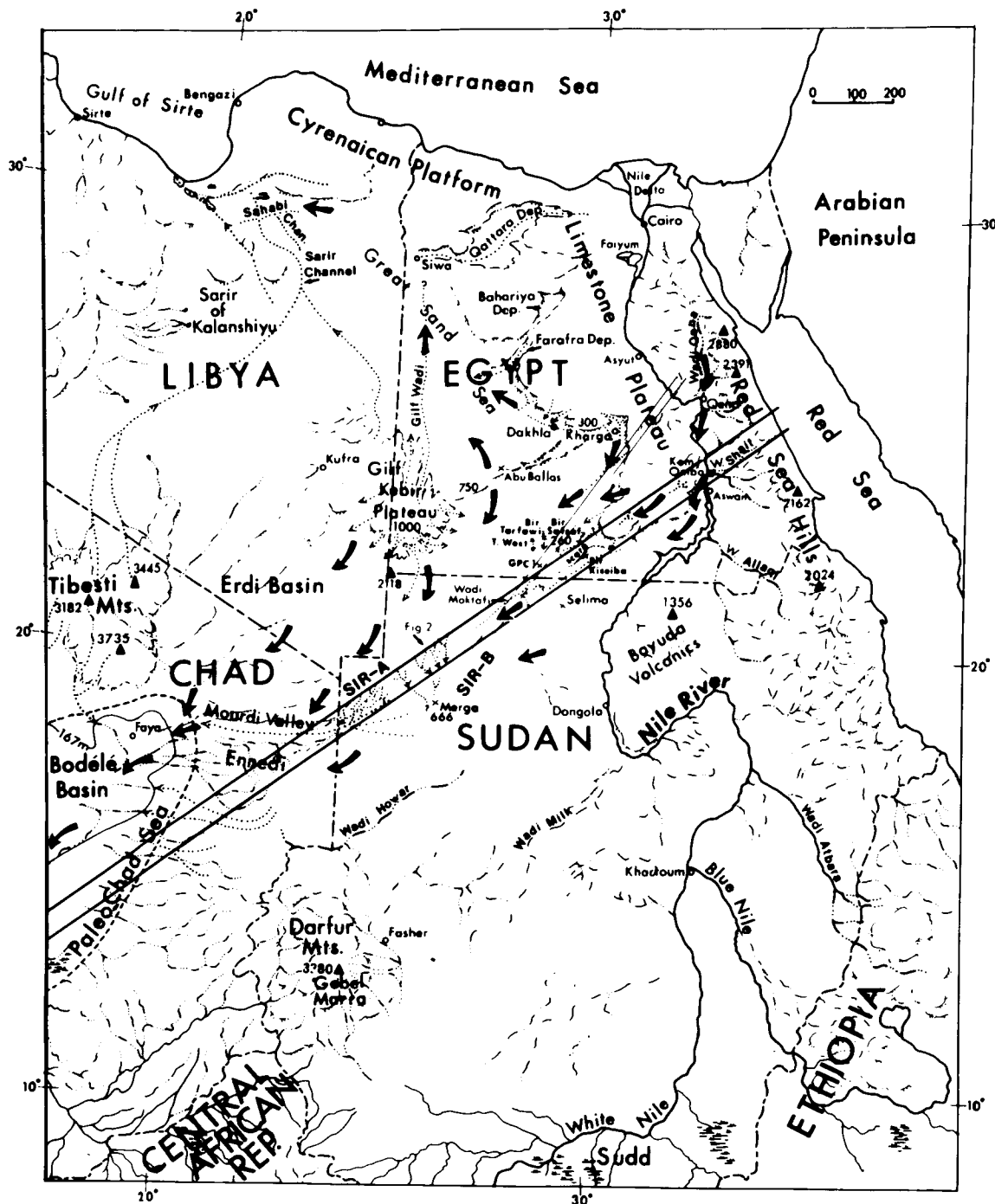


Figure 2. Map of Eastern Sahara, showing existing drainages with conventional symbols, and reconstructed paleodrainages with dotted lines. Paleodrainage north, south, and west of Kufra, Libya, from recent literature. Other reconstructions based on analysis of SIR-A, SIR-B and Landsat imagery, and field investigations. Large arrows show major drainage gradients inferred for mid-Tertiary time.

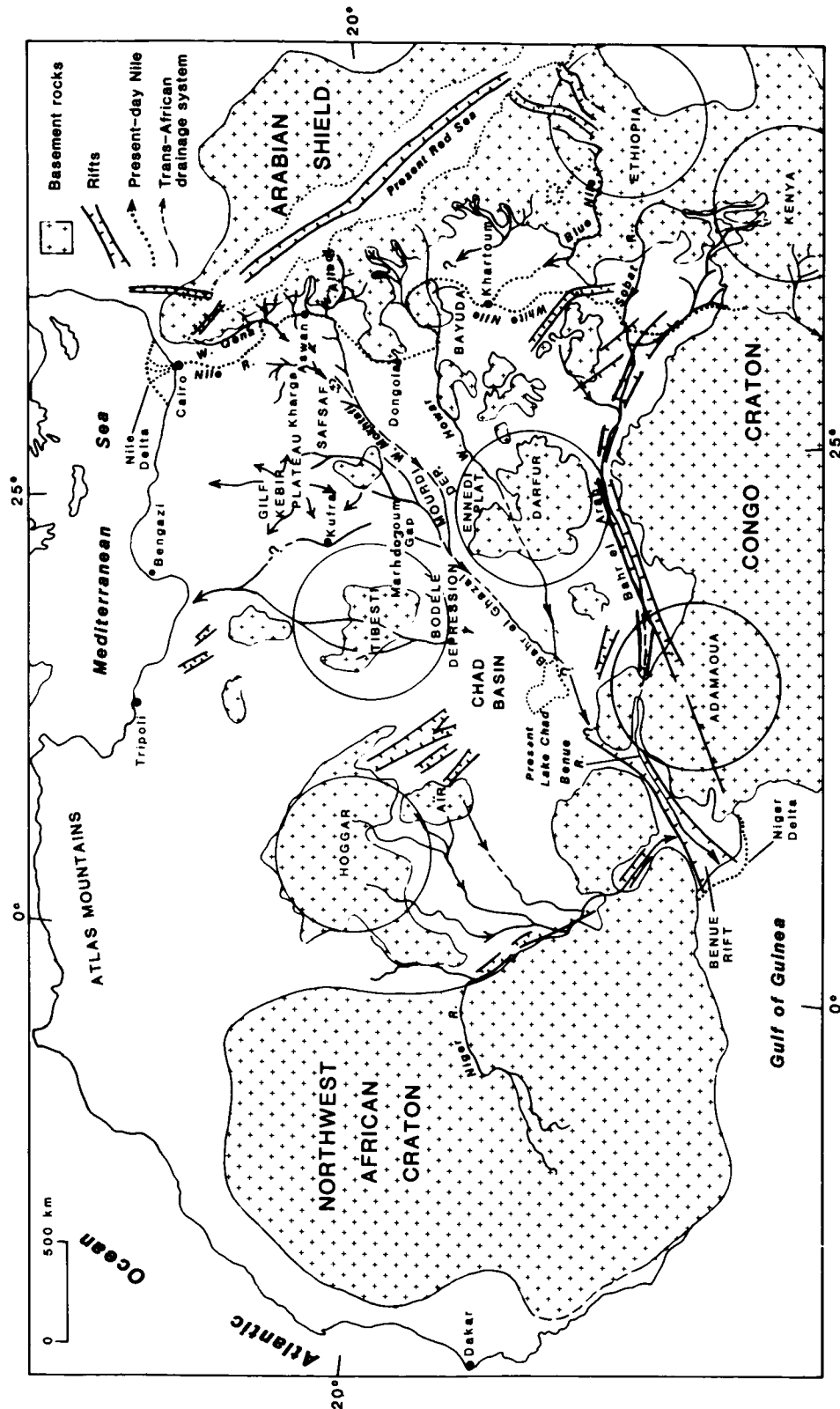


Figure 3. Major elements of proposed Trans-African Drainage System (TADS) as they may have existed at the time of its climax in the middle Tertiary. Circles indicate major centers of intracratonal doming and volcanism that disrupted TADS starting in middle to late Tertiary time, causing local ponding and drainage reversals. The present northeastward regional gradient in Egypt was probably not established until at least the late Miocene when the Nile Canyon was formed in response to drying up of the Mediterranean.